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Automatic Crack Recognition System for Concrete Structures Using Image Processing Approach

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Abstract: Recently, digital image processing technologies have been widely applied in different industries, because computerized technologies were widely utilized. In performance evaluation of deteriorating concrete bridges, the defect recognition such as crack pattern, crack width, crack depth, etc. On concrete surface is a significant advance and may lead to automation of the existing concrete bridge inspection at primary stage of the diagnosis. This study describes a novel approach for developing a system that extracts a crack pattern from digital images. A characteristic feature of the system is the use of an interactive genetic algorithm to optimize some parameters involved in the digital image processing. The algorithm prevents the system user from adjusting the parameters by trial and error. The user only evaluates some images produced by the system. The effectiveness of the system is verified by comparison of the results processed by trial and error and those obtained by using the proposed system. Once the above mentioned crack pattern on the concrete surface can be recognized, this study also introduces, in addition to an automatic measuring method of the maximum crack width, a practical recognition expert system which performs automatically with a certain level of accuracy.

Key words: Automatic crack, recognition system, concrete structures, algorithm, image, parameters

INTRODUCTION

Infrastructure systems including numerous concrete structures in the world have to be prudently managed for balancing the safety, economy and sustainability requirements, then, maintenance of such infrastructure systems has become a major social concern. As a means of inspection for maintenance, visual inspections are generally carried out to draw a sketch of defect (Japan Society of Civil Engineers, 2001). The records of the degree of defect vary depending on the judgment of the inspector. Poor skills may lead to faulty diagnoses. At present, therefore, advanced tools for visual inspection are required.

In this study, a prototype system was developed that could ultimately help automatically draw a sketch of defect. The defect sketching support system automatically identifies the defect on concrete surfaces. Once the defect sketching support system has been put to use on structures, drawing a sketch of defect will be made possible by simply using the photographs that are taken using a digital camera. Thus, the efficiency of inspection will be increased, inspection accuracy and reliability enhanced. Computer processing will then enable appropriate evaluation of the condition of the structure. This study describes the method for measuring defect using the images taken by a digital camera (Cho *et al*., 1999). The authors are currently concentrating their efforts on the study of "cracking", the most important type of defect of concrete structures.

This study proposes a method for measuring the crack width, one of the parameters for assessing deterioration of a concrete structure (Tian *et al*., 1986). The crack width measured using a gauge is compared with the value measured by the System. Then, the effectiveness of the System for measuring crack widths is verified. Cracks 0.2 mm wide or larger are considered to be detrimental to concrete structures (Japan Concrete Institute, 1987). In this study, therefore, a prototype system (the system) is developed to accurately calculate the widths of cracks 0.2 mm wide or larger by employing image processing technology.

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DEFECT SKETCHING SUPPORT SYSTEM

Inspection of concrete structures: The objective of a defect sketching support system is to enhance the reliability and precision of data sketching when required for inspecting concrete structures by using computers. If a defect sketching support system is to draw sketches equivalent or superior to those based on visual inspections, it should be designed to be able to recognize all the defects appearing on concrete surface. This study focuses on cracking, which is the most important type of defect detectable at the surface. This study therefore discusses a crack sketching support system, a specific application of the defect sketching support system.

Components of crack sketching support system: (Hamamura and Sato, 2000; Sasaki *et al*., 2001; Oka *et al*., 1999; Scheffy, 1999) Crack sketching support systems aim at measuring the location, width and extent of surface cracks that are required for diagnosing deterioration processes of concrete structures and digitizing the data and drawing a sketch quickly. A crack sketching support system is composed of a digital camera that photographs the concrete surface and a personal computer and relevant software for processing the image data. Figure 1 shows a flow chart of sketching the cracking condition. In the input phase, photographs are taken of cracks and the original images are provided to a computer. Then, the images are subjected to geometric calibration. The step involves correcting the skewness of each photograph and integrating the photographs. In the crack recognition phase, the characteristics of the cracks are identified and visualized. In the measurement phase, the widths and lengths of the recognized cracks are measured. Finally, a sketch of the cracks is output.

The following study describes the measurement phase in the flowchart in Fig. 1 in particular. The method for calculating the crack widths from the images of recognized cracks was examined and a prototype system was developed.

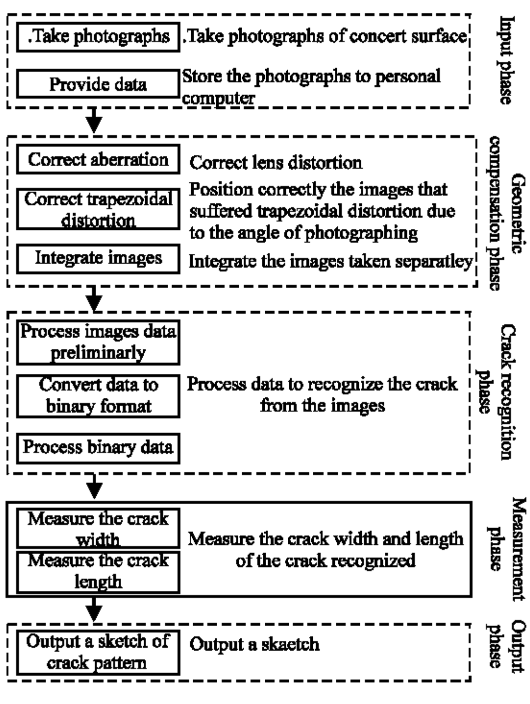

Fig. 1: Flowchart of crack skatching support system

DETERMINATION OF CRACK WIDTHS

Crack width determination procedure: In this study, the crack width is determined based on the difference of brightness which refers to the difference in brightness in cracked and non-cracked (background) areas. A flow chart for determining the crack widths is shown in Fig. 2 for a mean crack width in a selected local area. A detailed explanation of the flowchart.

Preliminary processing for crack width determination: (Sakai, 1997; Murakami, 1996; Tamura, 1997; Nagy *et al*., 2001). In the preliminary processing, original images are converted to a format fit for measuring the crack widths. Data required for crack width measurement are also collected such as the angle of the crack and the brightness of the background. The flow chart of preliminary processing for crack width measurement shown in Fig. 3 describes an algorithm for the preliminary

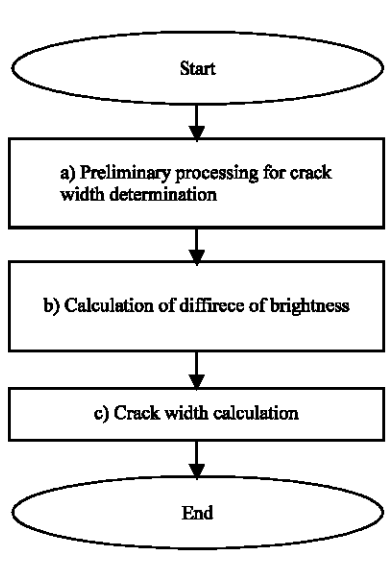

Fig. 2: Flowchart of crack width determination steps

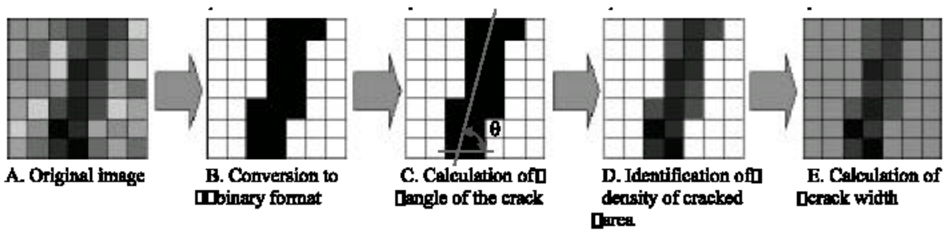

Fig. 3: Preliminary processing for crack width determination

processing for crack width measurement. Step (1) through (4) correspond to the steps of the same numbers in Fig. 3.

(1) The cracked area is recognized first by converting the original images to the binary format in the crack recognition phase shown in Fig. 1. The prototype system at the present stage of development, however, cannot completely recognize the cracked area in the crack recognition phase. The pixels around the cracked area are, therefore, also identified by expanding the binary images. This ensures the recognition of the cracked area. There occurs only a small error in crack width calculation owing to the characteristics of difference of brightness,
(2) An approximate straight line is drawn for cracking through the Hough transformation of the image. Then, the angle of the crack is obtained from the angle of the approximate straight line.
(3) The brightness of the pixel in the cracked area in the binary image is identified from the original image. Subtle difference in shade of the pixel in the cracked area enables more accurate calculation of crack width than from binary images.
(4) A certain brightness determined from the one-pixel outline of the binary image (adjacent to a zero-pixel location) is used as the uniform background brightness. This reduces errors in the calculation of brightness difference where the pixel in the cracked area contains information on the background.

Calculation of difference of brightness: In the study where the crack width is found to be too narrow to be expressed by a single pixel or a boundary is found between the crack and the background in a pixel as a result of photographing of concrete, the shade of the pixel of the digital image is expressed based on the percentage of the cracked area in a pixel (Fig. 4). The difference of brightness is the sum of differences in brightness between the concrete and the cracked area. The difference of brightness is, in other words, equivalent to the area of the shaded area in the graph of brightness in Fig. 4. Crack width is then calculated from the difference of brightness.

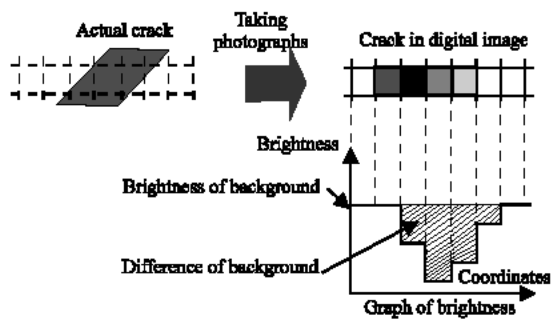

Fig. 4: Image of diffirence of brightness

The difference of brightness is obtained by the following procedure. The difference between the background brightness and the brightness of the pixel under study is totaled per pixel in a given row in the selected area. The sum of the differences of brightness in the row is the difference of brightness for the row. The difference of brightness, background brightness, pixel in row x and column y and width of a selected area are represented by DOB, Back, Pixel (x, y) and Width, respectively. Then, the processing is expressed by:

$$DOB = \sum_{x=0}^{Width-1} (Back - Pixel(x,y)) \quad (1)$$

The processing is carried out for all rows in the selected area. A mean difference of brightness is calculated from the differences of brightness for all rows. The mean difference of brightness is used to calculate the mean crack width in the selected area. The mean difference of brightness and the height of the selected area are represented by DOB_Ave and Height, respectively. Then, the mean difference of brightness is obtained by

$$DOB\_Ave = \frac{\sum_{y=0}^{Height-1} \sum_{x=0}^{Width-1} (Back - Pixel(x,y))}{Height} \quad (2)$$

where, both of Width and Height are applicable to the case where the pixel is scanned horizontally. When the crack is nearly parallel to the horizontal direction of the image, the pixel is scanned vertically. In the case of vertical scanning, the values of Width and Height are interchanged with each other.

Crack width calculation: In the crack width calculation phase, the crack width is calculated by calibrating the difference of brightness calculated under various conditions. The following factors influence the relationship between the difference of brightness and crack width.

- Crack width (e.g., the larger the difference of brightness, the larger the crack width).
- Angle of view (e.g., the larger the angle of view, the smaller the difference of brightness).
- Background brightness (e.g., the higher the background brightness, the larger the difference of brightness).
- Angle of crack (e.g., the more in parallel with the horizontal direction of image the crack is, the larger the difference of brightness).

If the above factors are taken into consideration, the crack width is calculated from the difference of brightness using

$$\text{Crack} = \text{DOB\_Ave} \times \alpha \times \beta \times \gamma \tag{3}$$

Where, Crack is the crack width, α, β and γ are correction factors for differences in angle of view, background brightness and angle of crack, respectively. In order to investigate the relationship between α, β and γ, a test was conducted using a drawing paper on which lines of different thickness were printed (the lines represented pseudo cracks). The widths of pseudo cracks were measured from the images of the pseudo cracks obtained with a digital camera (Fig. 5). The accuracy of crack width calculation was found to be greatly influenced by the performance of the digital camera used, photographing condition and the mode of photographing. The specifications of the digital camera used in this study and the photographing condition are listed in Table 1. The influences of α, β and γ were examined by varying any one of them while keeping the others fixed.

Relationship between crack width and difference of brightness for varying angle of view: The relationship between the crack width and difference of brightness was investigated by taking photographs while fixing the background brightness at 128 bits in gray scale and

Table 1: Photographing conditions

Date	2003/1/24
Weather	Cloudy
Camera used	Canon EOS-D30
Effective number of pixels	Approximatley 3011 maga pixels
Size if image	2160×1440
Image quality mode	Fine
Angle of view	0.5 through 2.0 m at intervals of 0.25 m
ISO sensitivity	ISO 100

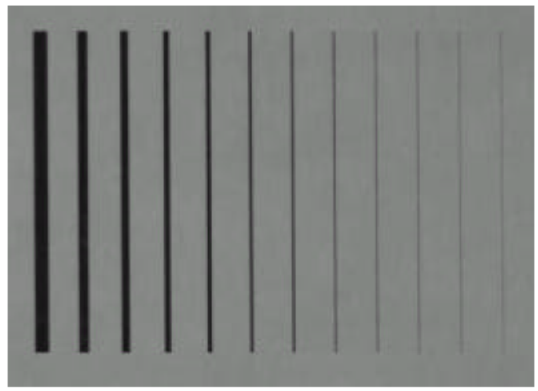

Fig. 5: Example of pseudo cracks

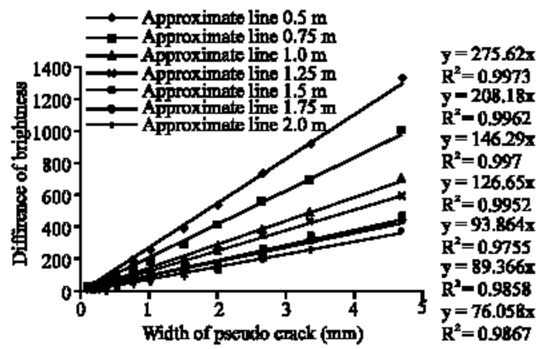

Fig. 6: Relationship between pseudo crack width and diffirence of brightness

varying the angle of view for pseudo crack from 0.5-2.0 m at intervals of 0.25 m.

The results in Fig. 6 show that the width of pseudo crack is nearly in proportion to the difference of brightness. The resultant approximate straight line is expressed by

$$\text{DOB\_Ave@} = \text{K} \times \text{Crack} \tag{4}$$

Where, K is the coefficient of angle of view, which indicates the slope of the approximate straight line in Fig. 6. The relationship between the angle of view AOV and K is expressed as shown in Fig. 7. The approximate straight line is expressed by:

$$K = @ = 148.85 \times AOV^{-0.9523} \quad (5)$$

Figure 7 suggests that the angle of view is nearly in inverse proportion to the coefficient of the angle of view. That is, the product of multiplication of the angle of view and the coefficient of angle of view is almost constant. The average of products of multiplication of the angles of view and the coefficients of angle of view shown in Fig. 7 is used as the coefficient of AOV in Eq. 5. The angle of view is in inverse proportion to the coefficient of angle of view, so the coefficient of angle of view K is expressed by

$$K = @ = 149.953 \times AOV^{-1} \quad (6)$$

Substituting 0.5 in AOV produces a K value of 299.906. Assuming the basis for calibration of the angle of view at an angle of 0.5 m, Eq. 4 is transformed to

$$DOB\_Ave@ = \frac{149.953 \times AOV^{-1}}{299.906} \times Crack \quad (7)$$

It is organized into

$$Crack = 2 \times AOV \times DOB\_Ave \quad (8)$$

Where, $2\times AOV$ in Eq. 8 is α.

Relationship between background brightness and difference of brightness: The background brightness was varied using pseudo cracks of different background color while keeping the angle of view and the width of pseudo crack fixed (angle of view: 0.5 m, width of pseudo crack: 1.0 mm). The results shown in Fig. 8 indicate that the difference of brightness is nearly in proportion to background brightness. Then, the relationship between the difference of brightness and the background brightness at an angle of view of 0.5 m is expressed by

$$DOB\_Ave = 2.1138 \times Back \times Crack \quad (9)$$

It is transformed into

$$Crack = \frac{1}{2.1138 \times Back} \times DOB\_Ave \quad (10)$$

where, $\frac{1}{2.1138 \times Back}$ in Eq. 10 is β.

Relationship between the angle of crack and difference of brightness: When the crack is slanted in the image, the crack width is measured as shown in Fig. 9. It was assumed that the crack width could be corrected by multiplying the difference of brightness by cosine where the crack was slanted. In order to verify the assumption, the following test was conducted.

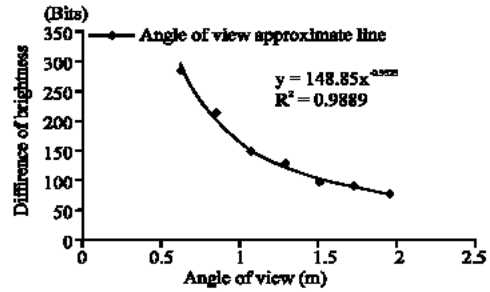

Fig. 7: Relationshipbetween pseudo crack width and diffirence of brightness

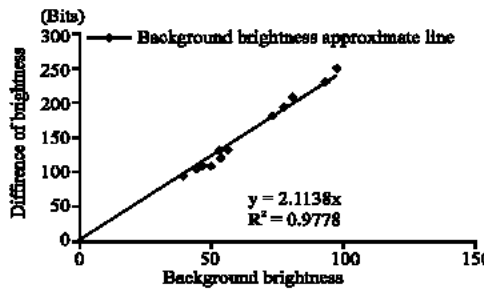

Fig. 8: Relationship between background brightness and diffirence of brightness

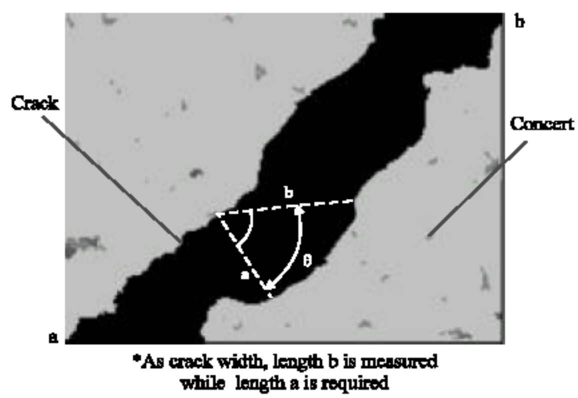

Fig. 9: Measurement of crack width at a great angle

Photographs were taken while keeping the angle of view (0.5 m), width of pseudo crack (1.0 mm) and background brightness (128) fixed and varying the angle of pseudo crack. The results are shown in Fig. 10, in here θ indicates the angle to the horizontal direction of the image. An angle of 90 degrees means that the crack is perpendicular to the horizontal direction of the image.

Errors according to the angle can be corrected by multiplying the calculated brightness by cos θ. Errors of difference of brightness are likely to be significant at an angle of 45 degrees or less. When the crack is slanted at an angle of 45 degrees or more, horizontal scanning is carried out. When the angle exceeds 45 degrees, vertical scanning is adopted.

Calculating crack width from difference of brightness: Based on the above results, an equation is deduced for calculating crack width from the difference of brightness. Substituting the values obtained above for α, β and γ, Eq. 3 produces:

$$\mathrm{Crack} = 2 \times \mathrm{AOV} \times \frac{1}{2.1138 \times \mathrm{Back}} \times \cos\theta \times \mathrm{DOB\_Ave} \quad (11)$$

Calculating the integers of the equation results in

$$\mathrm{Crack} = \frac{0.946 \times \mathrm{AOV} \times \cos\theta}{\mathrm{Back}} \times \mathrm{DOB\_Ave} \quad (12)$$

Crack width calculation system: The crack width calculation system calculates crack width by processing binary image data following the steps in the flowchart shown in Fig. 2. The computer screen for system implementation shown in Fig. 11 is outlined.

Original image: The original image opened from file is displayed.

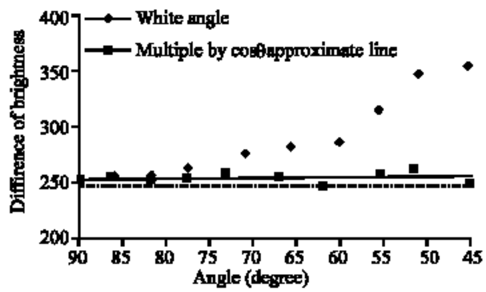

Fig. 10: Relationship between angle and diffirence of brightness

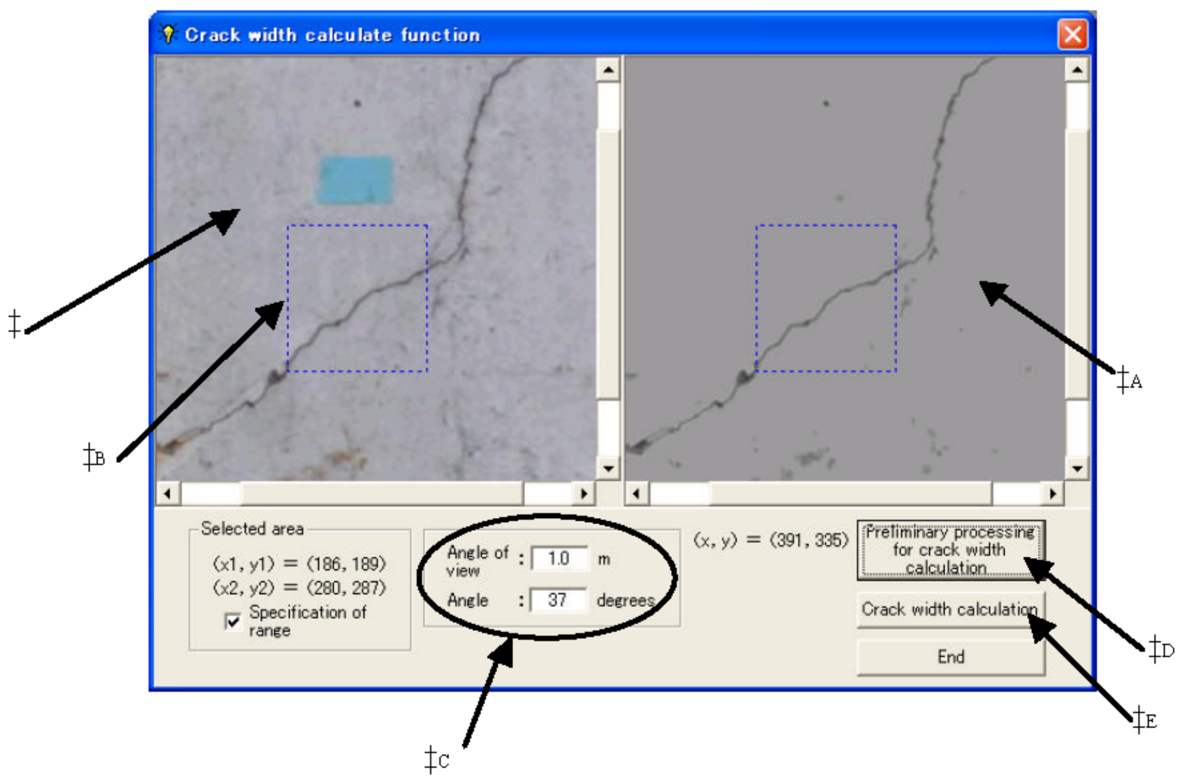

Fig. 11: Computer screen for executing width calculation system

Processed image: The image converted to the binary format in the crack recognition phase is displayed.

Specification of range: The range in which crack width is calculated is specified by the user.

Angle of view and angle of crack Specifying the range automatically leads to the display of the angle of the crack. The angle of view is input manually by the user.

Preliminary processing for crack width calculation: The binary image displayed in step (ii) is converted to a format suitable for calculating crack width.

Calculation: Difference of brightness is calculated and crack width is calculated accordingly.

SYSTEM VERIFICATION

The effectiveness of the prototype of crack width calculation system developed in this study is verified.

Table 2: Results of crack width calculation

Measurement	Calculation result	Error
Angle of view of 0.5 m		
0.2	0.2	0
0.25	0.2	-0.05
0.3	0.3	0
0.35	0.3	-0.05
0.45	0.5	0.05
0.6	0.7	0.1
1	0.8	-0.2
1.7	1.75	0.05
Angle of view of 1.0 m		
0.2	0.2	0
0.25	0.15	-1.0
0.3	0.25	-0.05
0.35	0.3	-0.05
0.45	0.4	0
0.6	0.9	-.1
1	0.9	-0.1
1.7	1.55	-0.15
Angle of view of 1.5 m		
0.2	0.35	0.15
0.25	0.25	0
0.3	0.25	-0.05
0.35	0.35	0
0.45	0.35	-0.1
0.6	0.7	0.1
1	0.75	-0.25
1.7	1.5	-0.2
Angle of view of 2.0 m		
0.2	0.4	0.2
0.25	0.4	0.15
0.3	0.25	-0.05
0.35	0.35	0
0.45	0.4	-0.05
0.6	0.5	-0.1
1	0.5	-0.5
1.7	1.1	-0.6

Method of verification: The crack width determined using the algorithm represented in the flowchart shown in Fig. 2 was compared with the actual crack width measured by a crack width measuring instrument (optical crack gauge). The result is shown in Table 2. The errors represent the variances between the calculation and measurement results by the optical crack gauge. The cases where the calculated width was smaller than the measurement are indicated by negative figures in the error column. Four images at angles of view of 0.5, 1.0, 1.5 and 2.0 m were used per crack.

DISCUSSION

At large angles of view, the calculated widths of thin cracks were larger that the measurements. The point is discussed below in terms of the three parameters used for calculating crack width.

Errors related to the angle of view: Errors may have occurred because the digital camera fully recognized 0.2 mm cracks at an angle of view of 0.5 m but failed to accurately recognize 0.2 mm cracks at an angle of view of 2.0 m. The calculated crack width was larger than the measurement at large angles of view probably because cracking was not completely recognized.

Errors related to the background brightness: The brightness on concrete surface is basically not uniform because of variance in material properties and formwork treatment, fouling or other types of defect. In this study, the brightness in the uncracked area was assumed uniform for calculating the difference of brightness. Under this assumption, images are expanded to increase the accuracy of crack recognition. For calculating the crack width, therefore, data are collected not only on the pixels in the cracked area of the original image but also on the pixels in the vicinity. The shade of pixel surrounding the crack has no significant impact at small angles of view. Where the angle of view is large and the crack is thin, the crack width is calculated from a few differences of brightness. In view of this, the data on the concrete surrounding the crack may have caused errors.

Errors related to the angle of crack: The cracks in concrete structures are neither straight nor of a uniform width. Therefore, a mean crack width in a certain area is calculated to reduce errors. The difference of brightness is, however, reduced where the angle of view is large and the crack is thin. Crack width calculation may have been affected because the crack was not straight.

Finally, the effectiveness of the system is verified as follows: Based on the results of Table 2, the crack width calculation method based on this study is considered satisfactorily effective as long as photographs (at present it needs to more than 2.160×1.440 pixels for resolution of the digital camera) are obtained as accurately as visual inspection, or at an angle of view of 1.0 m or less.

CONCLUSION

This study proposed a method for determining crack widths from the images taken from concrete surfaces by a digital camera. A prototype system was developed based on the method and the effectiveness of the system was verified.

The major results of this study are described:

- The difference of brightness in cracked (target) and uncracked (background) areas was obtained in an image of crack of a concrete structure. A method was proposed for calculating crack width from the difference of brightness.
- No unique crack width can be obtained even where the difference of brightness is uniform, because of the angle of view, brightness of concrete surface, the angle of the crack to the horizontal direction of the image or other factor. Certain correction is therefore necessary in crack width calculation based on the difference of brightness. In order to reflect varying conditions, pseudo cracks were represented by lines on a drawing paper. The effect of the pseudo cracks on the difference of brightness according to the photographing condition was investigated to deduce a correction equation for calculating crack width from the difference of brightness.
- The crack width calculated by the system was compared with the crack width obtained by manual measurement to verify the effectiveness of the System for crack width calculation. As a result, it was found that crack width could be calculated with few errors at an angle of view of 1.0 m or less. The errors of crack width calculation by the system were allowable and the system proved satisfactorily effective while conventional manual measurement also involves errors.

The tasks to be carried out are described:

- At present, the angle of view measured in advance during photographing needs to be input manually for calculating crack width. Recognizing the angle of view from the image taken seems difficult. A method will therefore be required for calculating crack width from other parameters than the angle of view such as the photographing distance and zoom lens magnification.
- The crack width calculated in this study is unique to the digital camera used. Using a different digital camera does not always produce the same result. The crack width calculation method should be revised so as to ensure uniform results regardless of the type of the digital camera used.
- Under the present system, a mean crack width is calculated in a cracked range specified by the user. For obtaining data on the location of the thickest part of a crack, therefore, the user needs to seek the thickest part in the image. Enabling the system to automatically recognize the cracked area and calculate crack width is likely to relieve the burden on the user.

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